Physical and Chemical Properties of Green Roof Media and Their Effect on Plant Establishment[1]

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Abstract

There are few research reports on components of green roof media. Better elucidation will allow landscape installers to select the ideal medium for individual or regional situations. The present study examined the effects of heat-expanded clay media components on: (1) physical and chemical properties and (2) growth of *Sedum floriferum* (stonecrop) and *Dianthus gratianopolitanus* (dianthus) plugs on a green roof. The addition of fine grade components caused an increase in bulk density and a decrease in total porosity, aeration porosity, and aeration porosity at applied suction pressure of 6.3 kPa. Container capacity reached a maximum following the addition of 40–60% (by vol) fine grade particles. Stonecrop and dianthus plugs were planted in early summer (June 29, 2010) into 6.4 cm (2.5 in) depth media containing 10–60% fine or medium grade heat-expanded clay located in a green roof garden. By early autumn (October 3, 2010), dianthus cover and plant weight were greatest in media containing 50–60% fine grade heat-expanded clay or 60% medium grade heat-expanded clay while stonecrop growth was inadequate regardless of media type.

Index words: vegetated roof, heat-expanded clay, *Sedum floriferum*, *Dianthus gratianopolitanus*, substrate.

Significance to the Nursery Industry

Landscape installers of green roofs use mineral-based media including heat-expanded slate, heat-expanded clay, heat-expanded shale, perlite, vermiculite, and/or sand mixed with 0–20% organic components such as peat moss, bark, and composted materials (2, 15). Germany has developed comprehensive green roof media standards (14) but such standards are lacking in the United States. Standards for the United States likely will be regional due to climate differences and availability of materials (2). It is important to note that procedures developed for landscape soil physical properties may not be applicable to green roof media. For example, using deep plastic 16.5 cm (6.5 in) cylinders for physical characteristic determination (14) will be of little value in determining physical characteristics of shallow depth green roof media. Since shallow depth green roofs have more widespread U.S. applications due to lower cost of installation and, possibly, lower maintenance costs (15), it is important to understand physical properties at these shallow depths. There is a need for more regional and practical research on individual components of green roofing technology (10). It is a disadvantage to the U.S. industry that much information is anecdotal, proprietary, or performed with non-replicated trials. It also is disadvantageous that much quality research is foreign with different climatic conditions and language barriers (10). A better understanding of physical, chemical, and plant growth effects may help landscape installers and clients decide which components are best to incorporate into their green roof media.

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Introduction

Benefits derived from green roofs include water retention and storm water management (3, 5, 37), energy savings, temperature management or insulation effects (7, 13, 27, 34), reduced noise pollution (36), increased biodiversity (20, 24, 31), and carbon sequestration (18). Other benefits include replacement of original vegetation that was lost due to the construction of the building and/or the potential to become an educational resource. Improved societal and aesthetic value also has been attributed to green roofs (16). Intensive (those containing media with a depth greater than 15 cm) and extensive (those containing media with a depth less than 15 cm) green roofs have different landscaping and maintenance needs (17).

Green roof media physical and chemical characteristics have not been well studied in the United States, although two industry reviews have summarized known information (2, 15). Compared to 5.0 and 7.5 cm (2.0 and 3.0 in) deep green roofs, 2.5 cm (1.0 in) depth green roofs have fewer species that can survive; Caucasian stonecrop (*Phedimus spurius*), goldmoss stonecrop (*Sedum acre*), white stonecrop (*S. album*), Chinese mountain stonecrop (*S. middendorffianum*), Jenny's stonecrop (*S. reflexum*), and tworow stonecrop (*S. spurium*) were capable of sustained growth on a 2.5 cm (1.0 in) depth green roof containing 40% heat-expanded slate, 40% sand, 10% peat moss, 5% dolomite, 3.33% composted yard waste, and 1.67% composted turkey litter (9). *Sedum floriferum* is an excellent green roof plant with 100% survival for both fall and spring plug plantings in shallow-depth media (17). Lanceleaf coreopsis (*Coreopsis lanceolata*) had higher survival percentages in 60 and 70% heat-expanded slate and less survival in 80–100% heat-expanded slate (30). Plant evaluations were conducted in Michigan environmental conditions with no supplemental irrigation after establishment (9, 17, 30). Herbaceous plant survival was reduced in heat-expanded shale compared to heat-expanded clay media and it was hypothesized that heat-expanded slate may cause similar poor growth in some species (35). Components within a heat-expanded slate media were a factor affecting growth of *S. floriferum* and *S. spurium* (26). Amendments to sandy loam soil were a factor influencing the green roof media physical properties and lantana (*Lantana camara*) growth and flowering (28).

In this study, we evaluated six green roof media with multiple components with varying percentages of fine and medium grade heat-expanded clay. By using a 6.4 cm (2.5 in) depth cylinder and applying a sub-saturation technique, we determined physical properties of media. In addition, we transplanted stonecrop and dianthus plugs into prepared media on top of a green roof (Ambler Arboretum of Temple University, Ambler, PA) and recorded visual ratings, plant cover, shoot dry weight, and media chemical properties (pH and EC) following a summer seasonal period.

Materials and Methods

Media components. Media components included fine, medium, and coarse-grade heat-expanded clay (Garick Corp., Cleveland, OH) consisting of particle ranges of 0.053 to 4.0, 2.0 to 9.5, and > 4.0 mm (0.0021 to 0.16, 0.079 to 0.37, and > 0.16 in) diameter (accounting for > 86% of particles by weight), respectively. Arboretum and greenhouse waste consisting of plant refuse, weed plants, leaf litter, turfgrass clippings, and greenhouse plants with horticultural media was collected from the Ambler Arboretum of Temple University (Ambler, PA), composted, sieved through a 1-cm diameter screen, and placed in an SS60R electric soil sterilizer (Pro-Grow Supply, Brookfield, WI) at 82C (180F) for 40 min (25). A majority (84.4%, by weight) of composted particles ranged from 0.053 to 4.0 mm (0.0021 to 0.16 in) diameter. Blended media consisted of 10:60:10:20, 20:50:10:20, 30:40:10:20, 40:30:10:20, 50:20:10:20, and 60:10:10:20 (%, by vol) fine grade heat-expanded clay:medium grade heat-expanded clay:coarse-grade heat-expanded clay:arboretum and greenhouse waste compost, respectively. Components were blended for five min in a cement mixer with Osmocote® Plus 15-9-12 controlled release fertilizer at 3.56 kg·m^{-3} (6.00 lbs·yd^{-3}; Scotts-Sierra Horticultural Co., Marysville, OH) followed by manual mixing. The fertilizer incorporation rate was selected based on manufacturer recommendations for a 3 to 4-month release in nursery media.

Physical properties. Physical properties of green roof media were determined in four replications at 0 and 6.3 kPa pressure. These values were selected based on Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau (FLL) recommendations (14) for testing physical properties of green roof media. Buchner funnel removable cylinders of 6.4 cm (2.5 in)-depth × 13.0 cm-diameter (volume capacity = 919 cm^3) containing one hydrated Whatmen#2 filter paper were filled with media (maximum of 1–3% variation in weight between replicates). The filled cylinders were tapped on a solid table surface ten times, topped-off with additional media, and subjected to procedures previously described (32, 39). Maximum water-filling of pore spaces was achieved through sub-irrigation using distilled water, which was added until media was saturated and surface appeared to glisten. Media were allowed to remain saturated for 24 h. Then, the cylinder and media were removed to a pan, and weighed. Total porosity was determined from the amount of water needed to saturate media. Media were allowed to drain for 24 h [21C (70F); 98% relative humidity] before being weighed and water retention determined gravimetrically. Container capacity equaled the amount of water retained after drainage divided by container volume followed by multiplication by 100. Aeration porosity equaled total porosity minus container capacity. A vacuum pressure apparatus (32) was constructed with a water reservoir to allow a 63 cm rise in water column within a 100-cm buret for media aeration porosity determination at applied pressure ($AP_{-6.3kPa}$).

Media particle size distribution was determined by screening using four replications of 100 g of air-dried samples placed into the top of a sieve series with mesh diameters of 9.50, 4.00, 2.00, 1.00, 0.50, and 0.053 mm. Each sample was shaken for three min with a Ro-Tap shaker (W.S. Tyler, Mentor, OH) and particles in each sieve and receiver pan were weighed and percentages determined. Summation curves (6) of green roof media and FLL distributions were created by plotting the logarithm of the mesh diameter (x-axis) versus the percentage of particles (wt:wt basis) which pass through the mesh (y-axis).

Plant growth. Seeds of stonecrop and 'Grandiflorus' dianthus (Jelitto Perennial Seeds; Schwarmstedt, Germany) were sowed onto double thickness No. 385 blotters (Seedburo Co., Chicago, IL) contained in 125 × 80 × 20 mm transparent polystyrene boxes moistened with 20 ml of distilled water and incubated as per requirements for *S. acre* (1). One week after sowing, seedlings were removed with forceps to Redi-Earth Plug and Seedling Mix (SunGro Horticulture, Bellevue, WA) contained in 288 plug sizes (one seedling per plug). Seedlings were fertilized every two weeks with 100 ppm nitrogen (N) alternating with 20-10-20 and 13-2-13 water soluble fertilizers for 8 weeks. Plugs were transplanted into 6 × 4 × 5.5 cm (length × width × depth) containers filled with general purpose peat-based media and fertilized once every three weeks with 150 ppm-N alternating with 20-10-20 and 13-2-13 water soluble fertilizers for an additional 9 weeks. On June 29, 2010, plugs were placed into Temple University's green roof (Ambler Arboretum of Temple University, Ambler, PA) containing the media treatments prepared as previously stated. The roof had an estimated slope of 15 degrees. Each replicated area was 84 × 30 cm (33 × 12 in) and plants were spaced 10.2 to 12.7 cm (4 to 5 in) apart from one another with four replications for each of the two plant species and six media. There were a total of twelve plants per repetition. Media depth was approximately 6.4 cm (2.5 in). Natural rainfall plus supplemental irrigation (hand watering) was 18.3, 7.1, and 19.8 cm (7.2, 2.8, and 7.8 in) for July, August, and September, respectively. Natural precipitation estimates were as per the National Weather Service (23). Mid-day photosynthetically active radiation (*PAR*) averaged 1190 µmol·m^{-2}·sec^{-1}. Minimum/maximum temperatures on the green roof surface were 17/46C (63/115F), 13/43C (55/109F), and 5/35C (41/95F) for July, August, and September, respectively. Plant cover was determined by a method reported previously (26). A photograph of each plant was taken using a 55 mm EOS Rebel XT digital camera (Canon Inc., Tokyo, Japan) 14 weeks after transplanting. Each photograph was taken directly overhead and included a 90 mm^2 standard; photographs and standard were printed, cut, weighed, and coverage area determined relative to the standard. The visual appearance of each plant was rated on a 1–5 scale: 1 = dead, 2 = plant stress evident and/or little change since transplanting, 3 = slow growth, 4 = healthy plant exhibiting a moderate amount of growth, and 5 = healthy plant growth and fullness. Shoots were cut at the surface of the substrate, dried at 70C (158F) for 48 h, and weighed. Pre- and post-experimental media samples were obtained for a 1:2 dilution test [1 media:2 distilled water (by vol)] for pH and EC determination using a pH Testr30 and EC Testr11 plus (Oakton Instruments, Vernon Hills, IL). The 1:2 dilution test is a common horticultural testing method for determining pH and EC (33).

Data analysis. Media experiments were arranged in a completely randomized design with four replications for each of the six treatments (media types). The plant growth experiment was arranged using a randomized complete block design with a split-plot arrangement of treatments (19) with six media (main plot treatments) and two plant species (subplot treatments). Data, where appropriate, were subjected to analysis of variance using PROC GLM (SAS 9.1; SAS Institute Inc., Cary, NC). Data were transformed (19) and means were separated by Fisher's protected least significance difference (LSD) at $P \leq 0.05$ or $P \leq 0.01$. Physical property data were analyzed for linear and quadratic regression trends.

Results and Discussion

A typical bulk density for an extensive green roof medium is 0.67 $g \cdot cm^{-3}$ (15). Soils with a high bulk density are subject to increased thermal conductivity (4); thus, green roof media with a low bulk density may result in less heat stress during summer months. In the current study, bulk density values increased linearly as the amount of fine-grade materials increased (Table 1). Values for heat-expanded clay mixes ranged from 0.68-0.77 $g \cdot cm^{-3}$ for media containing 10–60% fine-grade particles, respectively. Although bulk density was slightly higher than typical industry material, it was lower than other tested green roof mixes including sand-silt-clay with bulk density of 1.37 $g \cdot cm^{-3}$ (17), sandy loam soil plus urea-formaldehyde resin foam with a bulk density of 0.81 $g \cdot cm^{-3}$ (28), heat-expanded slate plus sand, poultry manure compost and composted yard waste with bulk density of 1.3 $g \cdot cm^{-3}$ (22), or heat-expanded slate plus compost with bulk density of 0.87–0.88 $g \cdot cm^{-3}$ (26). In general, the lower bulk density of heat-expanded clay media is desirable to minimize load on buildings.

German standards for green roof media (14) include: container capacity ≥ 35% (by volume) and aeration porosity > 10% (by vol) or $AP_{-6.3\ kPa} \geq 25\%$ (by vol); however, these values are determined using 16.5 cm (6.5 in) deep cylinders rather than the 6.4 cm (2.5 in) deep cylinders used in this study. Fine grade heat-expanded clay additions linearly and quadratically affected container capacity, attaining a maximum at 40–60% incorporation rate (Table 1). Although 40% fine grade heat-expanded clay medium had comparatively high container capacity (28.8%) some of this water was easily removed, as evidenced by high $AP_{-6.3kPa}$. Aeration porosity in a 28 cm (11 in) deep cylinder containing sandy loam ($AP_{-4.0kPa}$ = 21.9%) following mild suction pressure (28) was similar to 10–20% fine grade heat-expanded clay in a 6.4 cm (2.5 in) deep cylinder (Table 1; $AP_{-6.3kPa}$ = 19.0–19.7%) but the former had a higher total porosity (45.9%) than heat-expanded clay (37.5–38.0%). Since the drainage pressure is greater within the deeper cylinder, the sandy loam soil total porosity and aeration porosity likely would be reduced in a smaller cylinder. Except for short durations following irrigation, it may be that extensive media in actual green roof conditions are perpetually dry or nearly so (38); thus, high aeration porosity, or $AP_{-6.3\ kPa}$ values may be less vital for summer plant growth than adequate container capacity. The addition of fine particles resulted in linear decreases in total porosity, aeration porosity, and $AP_{-6.3\ kPa}$. Typically, the lower limit for gaseous diffusion through soil is 10% or through soilless media is 10–30% (29). A decrease of aeration porosity and/

Table 1. Total porosity, container capacity, aeration porosity, and aeration porosity at applied suction pressure of 6.3 kPa of heat-expanded clay-based media amended with arboretum and greenhouse waste compost.

Media components[zy]								
Fine grade expanded clay (%, by vol)	Medium grade expanded clay (%, by vol)	Coarse grade expanded clay (%, by vol)	Compost (%, by vol)	Bulk density ($g \cdot cm^{-3}$)[x]	Total porosity (%)	Container capacity [% (deg.)]	Aeration porosity [% (√%)]	Aeration porosity at applied suction pressure of 6.3 kPa [% (√%)][w]
10	60	10	20	0.68d[v]	37.5a	23.4 (28.9)d	14.0 (3.7)a	19.0 (4.4)a
20	50	10	20	0.68d	38.0a	24.9 (30.0)c	13.1 (3.6)a	19.7 (4.4)a
30	40	10	20	0.72c	35.6d	27.0 (31.3)b	8.6 (2.9)b	12.8 (3.6)b
40	30	10	20	0.72c	36.4c	28.8 (32.5)a	7.6 (2.8)b	16.1 (4.0)ab
50	20	10	20	0.75b	34.4d	29.1 (32.6)a	5.3 (2.3)c	8.1 (2.8)c
60	10	10	20	0.77a	33.8d	29.1 (32.7)a	4.6 (2.2)c	6.8 (2.6)c
Significance								
Linear				***	***	(***)	(***)	(***)
Quadratic				NS	NS	(**)	(NS)	(NS)

[z]Fine, medium, and coarse grade heat-expanded clay were purchased from Garick Corporation (Cleveland, OH). Osmocote® Plus 15-9-12 controlled release fertilizer (Scotts-Sierra Horticultural Co., Marysville, OH) was incorporated at 3.56 $kg \cdot m^{-3}$ (6.00 $lbs \cdot yd^{-3}$).

[y]Compost was made from waste materials collected from Ambler Arboretum of Temple University (Ambler, PA).

[x]Bulk density, total porosity, container capacity, aeration porosity, and aeration porosity at applied suction pressure of 6.3 kPa were determined in 919 cm^3, 6.4 cm-tall × 13.0 cm-diameter (2.5 × 5.1 in) cylinders. 1 cm = 0.3937 inch.

[w]pF = log (cm H_20); 1000 cm H_2O = 1 bar; 1 bar = 100 kPa.

[v]Mean separation within columns by Fisher's protected least significant difference (LSD) at $P \leq 0.05$.

deg. = angular transformation of percentage data (arcsin √%).

√ = square root transformation of percentage data.

***, **: $P \leq 0.001$, 0.01. NS: not significant.

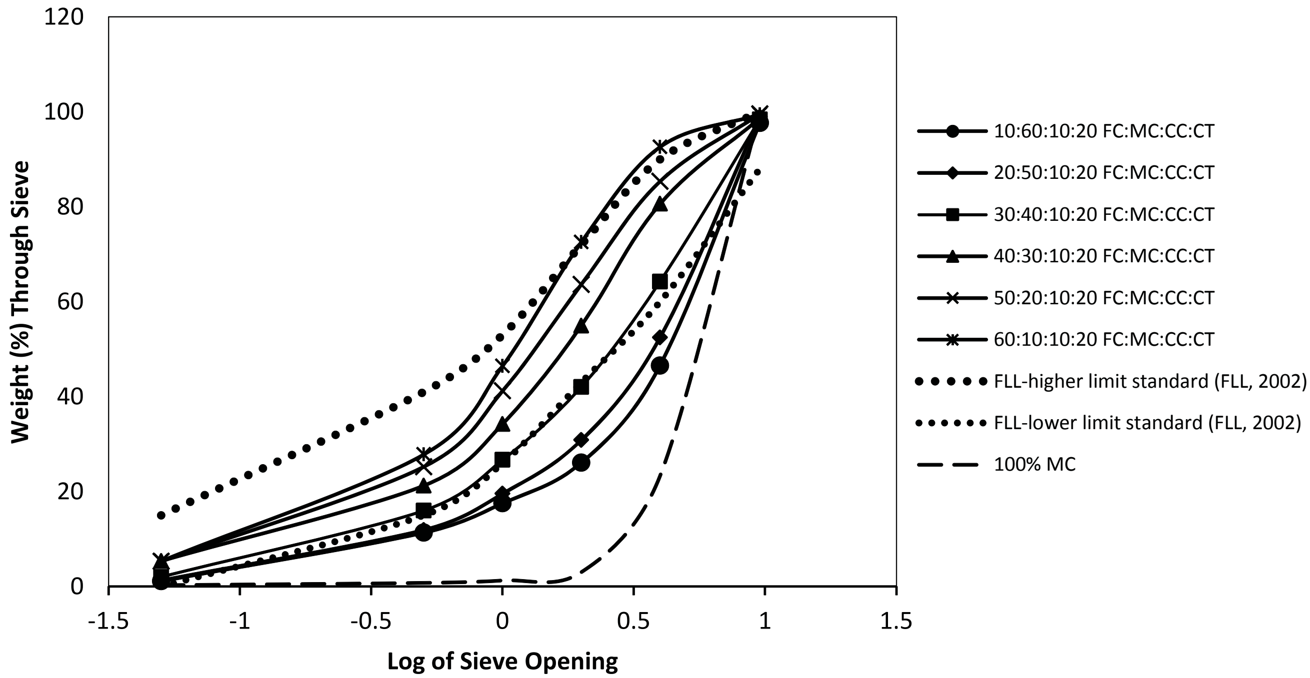

Fig. 1. **Particle size distributions of six blended media compared with German standards [Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau (FLL) e. V., 2002] for an extensive multiple component green roof. FC = fine grade heat-expanded clay; MC = medium grade heat-expanded clay; CC = coarse grade heat-expanded clay; and, CT = compost. Proportions of media components were blended based on volume. Mesh diameters of sieving pans were 9.50, 4.00, 2.00, 1.00, 0.50, and 0.053 mm. Datapoints indicate percentage of material passing through each sieve. Fine, medium, and coarse grade heat-expanded clay were purchased from the Garick Corporation (Cleveland, OH). Compost materials originated from arboretum and greenhouse waste materials of the Ambler Arboretum of Temple University (Ambler, PA).**

or $AP_{-6.3\ kPa}$ values in extensive green roof media recommendations would allow an inversely proportional increase in container capacity. It was reported that only high rates of hydrogel additions allowed greater than 35% container capacity values in small containers filled with heat-expanded slate media (26). A major concern, however, in decreasing particle sizes within green roof media is the effect on water permeability and potential for waterlogging. Green roof media must be highly permeable to ensure rapid removal of excess water (14). Sandy loam soil amended with peat moss and perlite had higher total porosity and $AP_{-4.0\ kPa}$, and moisture retention values than sandy loam soil, that resulted in winter waterlogging stress of lantana (28). Several succulents accumulated more biomass and coverage in proprietary media compared to 80–87% crushed roof tile-sand media with different physical and chemical properties (11).

Particle size summation curves are shown for recommended minimum/maximum FLL (14) extrapolations, for media containing 10–60% fine or medium grade heat-expanded clay, and for 100% medium grade heat-expanded clay (Fig. 1). Medium grade heat-expanded clay had 76.7% of particles that were greater than 4.0 mm. Fine grade heat-expanded clay had 92.9% of particles that were less than 4.0 mm and the distribution was within FLL standards with 100.0, 92.9, 61.7, 31.5, 15.4, and 1.2% of particles passing through 9.5, 4.0, 2.0, 1.0, 0.5, and 0.053 mm sieves, respectively. Particle size distribution provides an explanation for the higher total porosity, aeration porosity and $AP_{-6.3\ kPa}$ in media containing high percentages of medium grade heat-expanded clay (Table 1); the larger pores created by additions of medium grade heat-expanded clay, compared to fine grade heat-expanded clay, were easily drained or removed by 6.3 kPa suction pressure. By contrast, media with 60% fine grade heat-expanded clay had reduced overall total porosity but a greater ability to hold water following drainage at 0 or 6.3 kPa pressure.

Media type affected visual ratings, plant cover and dry weight (Table 2). *Dianthus gratianopolitanus* plant cover and dry weight were greatest in 60% fine grade heat-expanded clay media and exceeded *S. floriferum* growth by 4.4× and 9.4×, respectively. Researchers have suggested that summer establishment be evaluated for *S. floriferum* and other hardy succulents (17) but our results indicated that summer plug establishment for *S. floriferum* was poor. Enhanced growth of dianthus in 50–60% fine grade heat-expanded clay is in agreement with other research that determined visual rating improvement for green roof plants likely was due to higher media water-holding capacities (30). The reason dianthus growing in 10% fine-grade heat expanded clay performed better than those in 20–40% fine grade heat-expanded clay is unknown, but perhaps increased plant cover and dry weight occurred in the former due to less heat conductivity or to enhanced water penetration thorough the medium. Growth displacement between *S. floriferum* and *D. gratianopolitanus* may have occurred due to competition within media. It was noted that *S. middendorffianum* displaces *S. spurium* (30) and competition may cause individual performance reductions of *S. acre* and *D. deltoides* (8). Surviving dianthus generally were in good health while most *S. floriferum* were stressed. In general, many *Sedum* species are ideal for shallow depth green roofs (38) but spring is the optimal planting time (17). Flowering of dianthus occurred in 10, 20, 50, and 60% fine grade heat-expanded clay media whereas no *S. floriferum*

Table 2. **Visual ratings, plant cover, and dry weight of *Sedum floriferum* (stonecrop) and *Dianthus gratianopolitanus* ('Grandiflorus' dianthus) 14 weeks after transplanting into a green roof garden containing heat-expanded clay-based media amended with arboretum and greenhouse waste compost. All plants were subjected to natural summer green roof conditions with occasional hand-watering.**

	Media components[z,y]						
Plant species	Fine grade expanded clay (%, by vol)	Medium grade expanded clay (%, by vol)	Coarse grade expanded clay (%, by vol)	Compost (%, by vol)	Visual rating (1–5)[x]	Plant cover (cm^2)	Plant dry wt (mg/shoot)
Stonecrop	10	60	10	20	2.0 ± 0.4[w]	25.1 ± 13.9	845 ± 454
	20	50	10	20	2.0 ± 0.0	26.2 ± 9.6	447 ± 130
	30	40	10	20	2.5 ± 0.6	33.6 ± 17.1	1783 ± 889
	40	30	10	20	2.5 ± 0.3	56.4 ± 15.7	1099 ± 317
	50	20	10	20	2.3 ± 0.5	46.8 ± 17.6	820 ± 300
	60	10	10	20	1.8 ± 0.3	23.3 ± 10.0	600 ± 219
Dianthus	10	60	10	20	2.3 ± 0.9	60.0 ± 53.4	3454 ± 3139
	20	50	10	20	2.0 ± 1.0	28.9 ± 28.9	2058 ± 2058
	30	40	10	20	1.0 ± 0.0	0.0 ± 0.0	0 ± 0
	40	30	10	20	1.5 ± 0.5	10.5 ± 10.5	600 ± 600
	50	20	10	20	2.8 ± 1.0	82.6 ± 53.1	4679 ± 3059
	60	10	10	20	3.3 ± 0.8	103.3 ± 35.1	5627 ± 1886
Single degree-of-freedom contrasts							
Dianthus alone in 10, 50, and 60 vs. 20, 30, and 40% fine grade expanded clay					NS	*	*
Stonecrop alone in 30 and 40% vs. 10, 20, 50, and 60% fine grade expanded clay					*	NS	NS

[z]Fine, medium, and coarse grade heat-expanded clay were purchased from Garick Corporation (Cleveland, OH). Osmocote® Plus 15-9-12 controlled release fertilizer (Scotts-Sierra Horticultural Co., Marysville, OH) was incorporated at 3.56 $kg \cdot m^{-3}$ (6.00 $lbs \cdot yd^{-3}$) and plants received no subsequent fertilizer throughout the experiment.

[y]Compost was made from waste materials collected from Ambler Arboretum of Temple University (Ambler, PA).

[x]Visual rating were 1 = dead; 2 = plant stress evident and/or little change since transplanting; 3 = slow growth; 4 = healthy plant exhibiting a moderate amount of growth; and, 5 = healthy plant growth and fullness.

[w]Value indicates mean ± standard error.

*: $P \leq 0.05$. NS: not significant.

flowered. *Dianthus deltoides* is not as drought tolerant as other green roof plants and may require supplemental irrigation regardless of media depth (35). In contrast, *D. gratianopolitanus* plantings should be considered regionally because of its hardiness and long flowering times from spring through late summer. Even following a planting date of late June, dianthus performed satisfactorily if provided with adequate media and moisture. Overall, dominant particle sizes of either 70–80% fines/compost or 70% medium/coarse grades increased dianthus cover and dry weight compared to other media while stonecrop visual ratings increased when dianthus growth decreased.

There were no practical initial (pH range = 7.34 to 7.45) or final (pH range = 6.57 to 6.75) pH differences among media. Nonetheless, all media types had a pH reduction following the summer growth period. Acidic rain in the northeastern United States can lower green roof media pH but it is moderated close to neutral in heat-expanded clay media (15). Recommendations call for a pH of 6.5 to 8.0 for extensive multiple component green roof media (14). The compost pH of 7.15 ameliorated the higher pH effects of the heat-expanded clay materials (pH = 8.42 to 8.67). In this study, initial EC of heat-expanded clay media (397 to 526 $\mu S \cdot cm^{-1}$) was lower than other reported media. Starting EC concentrations for other media were 1.38 $mS \cdot cm^{-1}$ for sand:silt:clay (17), 1.71 to 2.23 $mS \cdot cm^{-1}$ for heat-expanded slate-based media with compost (26), 3.29 $mS \cdot cm^{-1}$ for heat-expanded slate amended with sand, peat, dolomite, and compost (9), and 2.10 $mS \cdot cm^{-1}$ for sandy loam soil amended with urea-formaldehyde resin (28). Controlled release fertilizers typically are used to reduce nutrient runoff (12) but EC can be a poor indicator of nutrient status when resin-coated granules are used because they release in response to temperature (21). We reported that slate materials mixed with Osmocote® yielded a higher EC (26) than heat-expanded clay-based materials mixed with similar Osmocote® concentrations. It is possible that some blended components abraded the resin-coated granules during mixing thereby releasing nutrients. The final EC for 10 and 50% fine grade heat-expanded clay media (182 and 235 $\mu S \cdot cm^{-1}$, respectively) was lower than initial EC (397 and 436 $\mu S \cdot cm^{-1}$, respectively) which may have been due to leaching and/or plant nutrient uptake. Excessive leaching of nutrients from green roofs (35) and low cation exchange capacity necessitates that fertilizer must be reapplied to media for adequate plant growth (2). Slow-release fertilizers are preferred to conventional fertilizers (12) with a low fertilizer application rate (50 $g \cdot m^{-2}$ or less) for stonecrop plants (30); however, the relative frequency of fertilizer reapplication is unknown.

In conclusion, we compared six different green roof media for particle size distribution, for physical and chemical characteristics, and for plant summer growth. Unirrigated 2 cm (0.8 in) deep heat-expanded slate green roof media may be dry as soon as 1 d after irrigation (38) so even minor media moisture retentive ability may have a major impact on plant survivability. Thus, aeration porosity and $AP_{-6.3\ kPa}$ are not as vital as water retention (higher container capacity and water infiltration) during summer growth conditions in the Northeastern U.S. region on shallow-depth green roofs. To avoid potential layering a dominate particle grade may be preferable within the green roof soil profile (i.e. 60% fine grade heat-expanded clay) rather than media with an equal mix of grades. The predicted result of layered media is air pocket formation and reduced water infiltration (4). Since the coarse grade component has the greatest potential to cause layering and poor water retention following drainage, it probably should not be considered as a major green roof component. Media with 50 or 60% fine grade heat-expanded clay were near the upper FLL recommended particle sizes for multiple component green roof media, which resulted in greater container capacity values as well as enhanced dianthus visual quality, plant cover, and dry weight following a summer growth period.

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